Journal of Cleaner Production 172 (2018) 3942–3954

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Assessing wood use efficiency and greenhouse gas emissions of wood product cascading in the European Union

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ARTICLE INFO

*Article history:*
Received 21 June 2016
Received in revised form
6 April 2017
Accepted 26 April 2017
Available online 6 May 2017

*Keywords:*
Cascading use
Woody biomass
Forest bioenergy
Resource use efficiency
GHG emissions reduction
Circular bioeconomy

ABSTRACT

Cascading use of biomass is a recognized strategy contributing to an efficient development of the bioeconomy and for mitigating climate change. This study aims at assessing the potential of cascading use of woody biomass for reducing GHG (greenhouse gas) emissions and increasing the overall wood flow efficiency in the European Union's forest and bioeconomy sectors. A scenario and life cycle approach was followed to quantify the potential benefits of cascading use of woody biomass. We started from a reference scenario in which (post-consumer) waste wood and paper are re-utilized for energy only (S0). Then we compared the reference scenario with two alternative scenarios, the current waste wood and paper recycling practices (S1) and the maximum technical potential to increase recycling of waste wood and paper flows (S2). Following a supply chain perspective, different stages of production were analysed, including forgone fossil-fuels substitution, optimization at manufacturing level and forest regrowth. Through cascading use, the wood use efficiency ratio (cascade factor) in the European wood sector would be increased by 23% (S0 vs S1) and 31% (S0 vs S2) and GHG emissions (cradle-to-gate energy use) would be reduced by 42% (28 Mt$CO_2$-eq/year) and 52% (35 Mt$CO_2$-eq/year) in scenarios S1 and S2. However, increased wood product cascading is counter effected in the short term by reduced savings in the energy sector by 49% and 48% (−43 and −42 Mt$CO_2$-eq/year) in scenarios S1 and S2 due to delayed availability of waste wood and waste paper fibers. This explorative study highlights the potential of cascading use of woody biomass in the wood production chains to contribute to a reduction of environmental impacts related to wood resource and energy use, but it also reveals trade-offs in terms of GHG emissions reduction, relevant especially in meeting short-term (2020–2030) renewable energy targets.



## 1. Introduction

In recent years, energy from renewable sources has regained importance, due to concerns on aggravating human-induced climate change, mainly caused by the combustion of fossil fuels. The consumption of wood fuels (or forest bioenergy) increased significantly especially in Europe in the past years (Bais et al., 2015; Heinimö and Junginger, 2009), and this trend is expected to increase further in the next decades. A major driver is the new target for renewable energy (at least 27%) and a 30% GHG (greenhouse gas) emissions reduction compared to 1990 level set by the EU for 2030 (European Commission, 2015). Wood and also agricultural biomass for energy play a significant role in the National Renewable Energy Action Plans (NREAPs) of the EU Member States and their future strategies to expand the use of bioenergy (Scarlat et al., 2015; Proskurina et al., 2016; European Commission, 2013) as well as in meeting Paris agreement on a 1.5 °C global temperature increase limit and Sustainable Development goals (Müller et al., 2015).

Woody biomass is also increasingly used as feedstock for biomaterials due to the growing interest in what is sometimes referred as "bioeconomy", an economy in which biomass displaces petroleum and other conventional materials (Keegan et al., 2013). Bioeconomy is seen as a key mechanism to shift towards a low carbon

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http://dx.doi.org/10.1016/j.jclepro.2017.04.153

economy because products made from biomass are typically considered to have lower environmental impacts with regard to GHG emissions than equivalent products made out of non-renewable sources (Petersen and Solberg, 2005). However, there are a number of unwanted environmental effects related to the bioeconomy transition. For instance, the bioeconomy will increase the demand of biomass in general, and competition for scarce wood resources (Hagemann et al., 2016) and trade-offs might occur. Thus, increased demand for forest bioenergy – in line with the growing interest in national bioeconomy strategies – might lead to increased pressures on wood resources and forest ecosystems. Wood harvest is associated with removal of standing trees from vulnerable forest ecosystems which can lead to disturbances of biogeochemical cycles (Schulze et al., 2012; Haberl and Geissler, 2000). Moreover, the increasing intensification of harvesting for industrial processes to support the bioeconomy may threaten other ecosystem services such as carbon storage, fresh water resourcing and nutrient reservoirs (Laudon et al., 2011). Also, the use of (woody) biomass for energy (including feedstock for production of wood pellets) should be evaluated for its merits versus any other raw material use (OVAM, 2015; Richter, 2016). Raw material uses are, for example, the use of wood for the production of wood based panels, wood pulp or new products within the bioeconomy. There is need for greater synergies, particularly given the fact that wood can be used for a range of products with higher added value than just energy. To promote these synergies to the fullest, only efficient conversion of biomass to energy should receive public support (European Commission, 2016).

Therefore, it is important to find ways to monitor bioeconomy activities and their related environmental impacts. In this context, increasing the efficiency of wood biomass conversions along the life cycle of wood products has a high potential to alleviate this increased pressure. A more efficient use of woody biomass can be realised by cascading use, i.e. the use of woody biomass first for higher-added value products, encouraging material recycling afterwards (i.e. increasing wood waste material input) and using discarded wood products for energy recovery at their end-of-life (Dornburg and Faaij, 2005). Following the waste hierarchy (European Commission, 2008), fresh wood fibres could have a cascaded use via a prioritized order: durable wood product manufacturing, extending service life times, re-use, recycling, bioenergy and disposal (Sikkema et al., 2016; European Commission, 2013).

“The principle of cascading use of biomass originates from the forestry sector and has been proposed to maximize resource efficiency and GHG emissions reduction”, as discussed by Keegan et al. (2013). The role of cascading use of woody biomass in a future bioeconomy is increasingly being highlighted in current European discussions, for instance, the Circular Economy (European Commission, 2014) and the European Union Forest Strategy (European Commission, 2013). In some EU member States, there have been efforts to incorporate the cascading concept into national regulation, for instance, it has been included in the (voluntary) sustainability criteria for solid biomass used for bioenergy production in the Netherlands, Belgium and Hungary (Brinkmann, 2013; Richter, 2016), and it has also been brought up in the German forest strategy 2020 (Federal Ministry of Food, Agriculture and Consumer Protection, 2011).

Cascading use of wood is well implemented in Europe's paper industry (CEPI, 2014), because paper products have already been using largely recyclable and reusable materials. Only a small fraction of paper products (20–22%) cannot be recycled or recovered directly (e.g. cigarettes paper, sanitary paper, archived printed materials, etc.; CEPI, 2014). The use of recycled paper (or post-consumer paper) in paper production increased significantly during the past decade (CEPI, 2015). On the other hand, cascading use of wood has not yet been widely implemented in Europe. For example, in the construction sectors, most European post-consumer wood waste (e.g. construction and demolition wood) is combusted or disposed of in landfill (Mantau, 2012; Alakangas et al., 2015; Erlandsson and Sundquist, 2014). The use of post-consumer wood waste in particleboard is one of the few practices for recycling post-consumer wood (EPF, 2010). A number of European countries have already been utilizing post-consumer wood waste for particleboard production. The share of recovered (post-consumer) wood in an average particleboard is ranging from 1% in Estonia to 95% in Italy (Vis et al., 2016; Weimar 2015). In other European countries like Switzerland and Sweden, the material use of post-consumer wood in particleboard on industrial scales has been insignificant (Vis et al., 2016). The production processes of other wood panels such as medium density fibreboard (MDF) and oriented strand board (OSB) have not been utilizing recovered (post-consumer) wood, mainly due to minor cost benefits, for reasons of product image (Höglmeier et al., 2016) and technical challenges (Vis et al., 2016).

While cascading use has been proposed for improving the resource use efficiency of biomass systems and GHG emissions reduction efficiencies via replacing fossil fuels, few studies exist that assessed integrated wood biomass material and energy systems in their overall efficiency with respect to resource and energy use (Dornburg and Faaij, 2005; Sikkema et al., 2013). The $CO_2$ emissions reduction of poplar wood cascading has been assessed by Dornburg and Faaij (2005). However, transportation of biomass materials, as well as the collection of waste materials were not considered in their study. Wood flows in Europe have mainly been analysed from resource use perspectives (Mantau, 2012) and few studies have investigated the GHG emissions reduction potential of recycled material utilization of the paper and particleboard sector. So far, studies have focused only on gate-to-gate life cycle analysis of manufactories (Saravia-Cortez et al., 2013; Laurijssen et al., 2010; Merrild and Christensen, 2009). The recycling efficiency within re-manufactories as well as the forest carbon sequestration potential have not yet been addressed. The latter is particularly important as increased cascading use of wood could theoretically reduce harvest pressures of forested ecosystems. Consequently, forest biomass carbon stocks remain intact. The bioeconomy is expected to give a boost to extending high-value biomass uses in the coming decades, and fostering cascading use of woody biomass.

This study aims at comprehensively assessing the potential of cascading use of woody biomass for reducing GHG emissions and increasing overall wood flow (or wood use) efficiency in Europe's forest and bioeconomy sectors from the harvesting stage until end-of-life of a wood or paper product. Social impacts and a cost-benefit analysis (or economic impacts) are outside the scope of our inventory. We focus on 28 Member States of the European Union and employ a scenario and life cycle approach to quantify the effects of fostered cascading use in wood processing chains in terms of input-output efficiency and GHG emissions reduction. The focus is on the following aspects: virgin wood material input substitution in the wood sector (i.e. paper and particleboard industries), fossil fuel substitution in the energy sector, and prevention of post-consumer wood wastes from landfill disposal. At the end, the GHG effects of maximizing product cascading and the wood use efficiency from forest harvest until the product end-of-life are discussed.

## 2. Materials and methods

In this study, the potential benefits of cascading use of woody biomass in the wood sector in terms of GHG emissions reduction and wood use efficiency gain has been assessed by applying Life

Cycle Assessment (LCA) and Material- and Energy Flow Accounting (MEFA). The analysis are built on a conceptual framework shown in Fig. 1, combining a single or short wood utilization chain with multi-stage or long wood utilization chains. In a short wood utilization chain (or single-stage use) the discarded wood products (e.g. lumber and paper) are directly combusted for energy generation (Fig. 1a) while in a long wood utilization chain (or multi-stage use) the wood products are used at least once, but usually more often, as a material (e.g particleboard and paper) before utilizing it for energy purposes (Fig. 1b). The wood utilization chains either consider post-consumer wood flows (e.g. construction and demolition wood) or post-consumer waste paper recycling.

### 2.1. Description of the scenarios under study

In this study, the global wood carbon (C) flows approach, as developed by Bais et al. (2015), has been used. For this approach, we took wood flow data for all 28 EU Member States (EU-28) into account. In our most theoretical reference scenario (S0), we did not assume recycling of paper waste and waste wood flows for manufacturing new products. The particleboard and different paper grades are produced from 100% virgin fibre and the recovered post-consumer fibres directly combusted for energy generation (Table 1). In a next step, we defined two scenarios of wood cascading use: (S1) the current state-of-the-art waste wood and paper recycling practises, and (S2) optimized future product cascading through maximum recovery and re-utilization of (post-consumer) waste wood and paper (Table 1). S1 is based on the actual wood flows data for EU-28 (Bais et al., 2015); the collection rate (i.e. the amount of waste wood and paper collected in a country divided by the product consumption in a country; CEPI, 2015) and re-utilization rate (i.e. the amount of waste wood and paper used in a production process divided by the total production of paper and particleboard; CEPI, 2015) are taken from CEPI (2015) and Mantau (2012) (Table A.1; see Appendix). In S2, the potential benefits of cascading use of woody biomass was assumed to maximize by optimizing the current cascading wood use via an integration of an intensified mobilization of post-consumer wood resources (i.e. increased collection and re-utilization rates) and zero waste (or prevention of landfill disposal) strategy. S0 follows a short wood utilization chain (or single-stage use) while S1 and S2 follow a combination of short and long wood utilization chains (or multi-stage use).

The assessment is mainly focused on particleboard and different paper grades such as newsprint, sanitary paper and packaging paperboard (e.g. corrugated board, grey board and folding boxboard) because these products can be produced from both virgin and recovered fibres. We assumed the same volume of wood and paper production in all scenarios. The share of recovered fibre in total paper and particleboard production is presented in Table A.1.

### 2.2. System boundaries and functional unit

Both cradle-to-gate and cradle-to-grave models were developed to enable a more comprehensive assessment of the GHG impacts of cascading use of wood. The cradle-to-gate model includes the roundwood (i.e. sawlogs and pulpwood logs) production and extraction (i.e. forest operations), the sawmill process, the post-consumer wastes recovery process, pulp and particleboard manufacturing processes and transport (Fig. 2). In contrast, the cradle-to-grave model includes post-consumer wastes collection and transport and two end-of-life (EoL) pathways: incineration with energy recovery and landfill disposal (Fig. 2).

To assess the cradle-to-gate GHG emissions reduction, we compared the particleboard and wood pulp production processes using virgin fibre material (i.e. wood which had no chemical treatments or finishes applied, e.g. industrial roundwood and sawmill co-products) with recovered fibre material (i.e. post-consumer wood and paper) (Fig. 2). The moisture content of recovered and virgin fibres can vary extensively (Merrild and Christensen, 2009; Sathre and Gustavsson, 2006). The moisture content of recovered and virgin fibres is here assumed to be 15–25% (average 20% used in this study) and 40–60% (average 50% used in this study), respectively. Recovered post-consumer wood mainly comprises demolition and construction wood and wood packaging materials. Recovered post-consumer paper includes used paper of different grades (e.g. writing paper, newsprint, packaging, etc.). We limited our inventory of GHG emissions in the manufacturing processes up to the point of wood drying (for particleboard production) and pulping (for wood pulp production). We assume the succeeding processes in the paper and particleboard manufacturing to be the same (with regards to processing energy use) whether the fibres are recovered or virgin.

The components added in the cradle-to-grave assessment include GHG emissions savings from fossil fuel substitution (i.e.

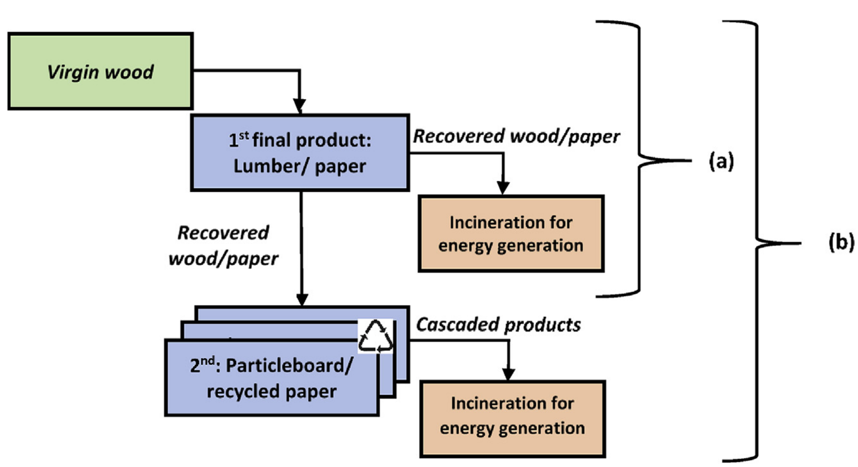


**Fig. 1.** The following cascading use stages (or wood utilization chains) are applied: (a) single-stage use (or short wood utilization chain), direct incineration of discarded wood products for energy generation; (b) multi-stage use (or long wood utilization chain), product recycling of discarded wood products before utilizing it for energy generation. (Adopted from Essel et al., 2014).

**Table 1**
Description of scenarios and related industries assessed in this study.

| Scenario | Description | | | | | |
|---|---|---|---|---|---|---|
| | Post-consumer wood pathways | | | Post-consumer paper pathways[a] | | |
| | Wood sector (Particleboard industry) | Energy sector (combustion for energy generation) | Waste sector (landfill disposal) | Wood sector (Wood pulp and paper industry) | Energy sector (combustion for energy generation) | Waste sector (landfill disposal) |
| S0. No product cascading (direct incineration of recovered paper and wood) | 0% collection rate with 0% re-utilization rate; 100% utilization of virgin wood | 70% (8.5 MtC/year) of the potential post-consumer wood (PCW) waste | 30% (3.5 MtC/year) of the potential PCW waste | 0% collection rate with 0% re-utilization rate; 100% utilization of virgin wood | All recovered post-consumer paper (PCP) waste (76%; (38 MtC/year) go to energy | 12% (6 MtC/year) of the potential PCP waste |
| S1. State of the art wood and paper recycling | 30%[b] (3.5 MtC/year) of the PCW waste with a re-utilization rate of 27% recovered fibres and the remaining 73% consists of virgin fibres based on 100% fibre fraction | 40%[b] (5 MtC/year) of the potential PCW waste | 30%[b] (3.5 MtC/year) of the potential PCW waste | 66% (33 MtC/year) of the potential PCP waste with a re-utilization rate of 51%[c] and the remaining 49% consists of virgin fibres | 10% (5 MtC/year) of the potential PCP waste | 12%[b] (6 MtC/year) of the potential PCP waste |
| S2. Optimized future product cascading (maximized product recovery and zero-waste strategy) | 45%[d] (5.4 MtC/year) of the potential PCW with re-utilization rate of 41% recovered fibres and the remaining 59% consists of virgin fibres based on 100% fibre fraction | 55% (6.6 MtC/year) of the potential PCW waste | 0% of the potential PCW waste | 78%[e] (39 MtC/year) of the potential PCP with re-utilization of 61% recovered fibre and the remaining 39% consists of virgin fibre | 10% (5 MtC/year) of the potential PCP waste | 0% of the potential PCP waste |

[a] Including 12% (6 MtC) export, assuming net trade remains the same in all scenarios.
[b] Mantau (2012).
[c] Re-utilization rate in 2010 taken from CEPI (2015).
[d] The technically maximum recovery of wood waste from deconstruction suitable for particleboard production is 45% which belongs to wood wastes' class AI (i.e. untreated wood) and class AII (i.e. glued or painted wood without halogen organic compound or preservatives) that could be used for material use without prior processing, according to Höglmeier et al. (2013).
[e] About 6 MtC/year of post-consumer paper waste is assumed to be diverted from landfill disposal to paper industry.

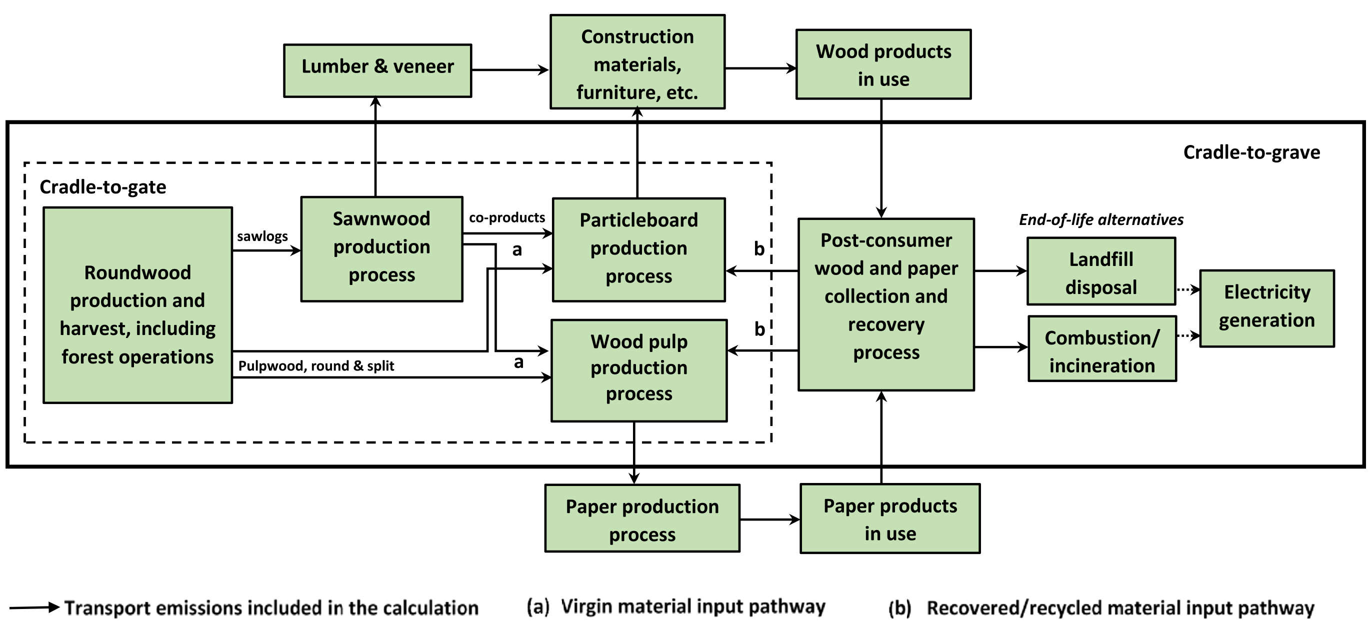


**Fig. 2.** System boundary of the paper and particleboard life cycle model followed in this study, showing the life cycle stages of wood pulp and particleboard manufacture by utilization of a) virgin fibre and b) recovered fibre as raw material input and the two end-of-life alternatives.

electricity EU mix from the grid) and from prevention of landfill disposal (see section 2.3.5 for details).

The functional unit was tonne wet weight woody raw material input for the production of particleboard, wood pulp for different paper grades and bioenergy (see Table A.2 in Appendix). The environmental impact category was global warming potential in kg $CO_2$ equivalents ($CO_2$-eq) including $CO_2$, $CH_4$ and $N_2O$ released during the life cycle (LC). The amount of energy required (per tonne wet weight woody raw material) by the different processing steps was multiplied with the emission factor of the specific energy carrier (Table A.3, Table A.4; see Appendix). The different units of woody raw material input (e.g. $m^3$ roundwood) and energy required in pulping and drying processes (e.g. MJ/tonne paper or MJ/$m^3$ particleboard; see Table A.3 in Appendix), were converted to (per) tonne wet weight woody raw material by using the conversion factors (Table A.5 in Appendix).

### 2.3. Life cycle stages & data elaboration

LC stages investigated in this study were roundwood production

and harvest (including forest operations), sawnwood production process, collection and recovery processes of post-consumer wood and paper, manufacturing process of paper and particleboard, transport and end-of-life alternatives. A full overview of the energy requirements per process in each LC stage is given in Table A.3 (see Appendix).

### 2.3.1. Roundwood production and harvest

The emissions associated with roundwood (virgin fibre) production and harvest, including forest operations, were taken from Dias and Arroja (2012) and Gonzalez-Garcia et al. (2009a,b). Both studies focused on the production of eucalyptus (*Eucalyptus* sp), maritime pine (*Pinus pinaster*), Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). These species are commonly used as raw materials for the forest and paper industries in Europe. According to the report of CEPI (2015), about 71% of the wood consumed in EU's paper industries is coniferous (or softwood) species, mainly pine (36%) and spruce (35%). Only 29% of wood consumed is non-coniferous or hardwood species: 14% birch (*Betula species*), 9% eucalyptus, 3% beech (*Fagus sylvatica*), 2% aspen (*Poplar* sp.) and 2% other hardwood. For the production of sawnwood, the coniferous species such as fir (*Abies alba*), spruce (together 64%), pine (23%), and the hardwood species such as oak (*Quercus* sp; 7.5%), beech (2.5%), birch (2%), aspen (1%) and ash (*Fraxinus excelcior*; 1%) are frequently used. This division is based on European import data in 2014, thus without domestic species (UNECE, 2015). A detailed overview of wood species for wood based panels, including veneer, is not reported to our knowledge.

The energy requirements for forest operations provided by Dias and Arroja (2012) and Gonzalez-Garcia et al. (2009a,b) has been presented in MJ/m$^3$ roundwood equivalent (rwe), without bark. The average bark percentage applied in this study is 12% (Dias and Arroja, 2012). Data on energy use for sawing logs for lumber production and mass allocation factor were taken from Puettmann et al. (2013).

### 2.3.2. Post-consumer wood and paper collection and recovery process

Post-consumer waste (recovered fibres) are assumed to be collected and transferred to the material recovery facility (MRF) for sorting and then transported to re-manufacturing mills. We here assumed that post-consumer wood is collected by truck (or lorry), and by forklift (Merrild and Christensen, 2009), and post-consumer paper is collected by a combination of different collection schemes such as co-mingled, full service (door-to-door), kerbside and/or drop-off containers (WRAP, 2009, 2011; Eisted et al., 2009; Larsen et al., 2009).

Transfer activities involve reloading, compaction, or even segregation of the waste which normally take place at transfer stations or MRF. Energy use for loading and unloading of recovered wood and paper by forklift was taken from Merrild and Christensen (2009). In MRF, the recovered paper is compacted by baling (0.10–0.162 kg $CO_2$-eq/tonne of baled waste; Eisted et al., 2009).

### 2.3.3. Wood pulp and particleboard production processes

The activities included in this life cycle stage are debarking, chipping, drying (only for particleboard production), pulping and de-inking (only for paper production). The energy required for debarking, chipping, and drying was taken from Saravia-Cortez et al. (2013) and Merrild and Christensen (2009). It was assumed that less chipping and drying energy is needed for recovered wood compared to virgin wood due to smaller size and lower moisture content of recovered wood compared with virgin wood (Merrild and Christensen, 2009).

The energy required for pulping of virgin and recovered fibres was taken from Laurijssen et al. (2010). Black liquor and paper sludge are by-products of pulping and de-inking processes of virgin and recovered fibres, respectively, which are combusted to produce energy. We assumed that the energy generated from combustion of black liquor produced from kraft chemical pulping, bark and recovered paper sludge (i.e. by-product of de-inking and re-pulping process) replaces electricity EU mix (from the grid) and steam (produced from natural gas) required in the pulping process. According to Laurijssen et al. (2010), the amount of generated heat through the black liquor recovery process in the kraft chemical pulping exceeds the heat demand of the process. The energy used to re-pulp recovered paper depends on the type of paper product and quality (e.g. de-inking, refining and dispersing steps). The amount of residue produced for each grade of paper depends on the source of raw material. The amount of paper sludge on a dry mass basis may vary from 7% to 40%, depending on paper grade (Bajpai, 2015, 2014; Scott et al., 1995). One tonne of waste paper sludge (dry basis) will generate 4.2 GJ steam (89% efficiency; Sikkema et al., 2013; Laurijssen et al., 2010) replacing natural gas fired in a combined heat and power (CHP) plant with 90% conversion efficiency (Laurijssen et al., 2010).

### 2.3.4. Transport

There are three main long-distance wood transport strategies to supply virgin roundwood to forest industries in Europe: road, railway and waterway. Road transport is the most important mode used for wood and represents 80–95% of the total tonnage of timber transported annually in the United Kingdom, France, Germany, Sweden and Finland (Le Net et al., 2011; Schwaiger and Zimmer, 2001). Rail transport (or train transport) is the second most important means of transport (Le Net et al., 2011; Gonzalez-Garcia et al., 2009b). Transport by ship is mainly used for long-distance domestic transport and imported wood (Gonzalez-Garcia et al., 2009b). We assumed that 80% of sawlogs and pulpwood logs are transported by road, 18% by rail and 2% by waterway: the allocation is based on the EU transport study of Le Net et al. (2011). The parameters used for secondary hauling (i.e. transport of wood from forest landing to mill gate) are taken from case studies in Spain, Sweden, Baltic countries and Germany (Gonzalez-Garcia et al., 2009a,b; Schweinle, 1996; Table A.3 in Appendix).

Recovered post-consumer wood and paper are assumed to be transported by lorry (16t weight capacity) from collection site to the MRF for sorting and finally transported by lorry (32t) to re-manufacturing mills, incineration power plants and landfills. The parameters for transporting post-consumer wood and paper is presented in Table A.3 (see Appendix).

### 2.3.5. End-of-life alternatives: incineration and landfill disposal

The post-consumer waste (i.e. used wood and paper) is directly transported to the incineration plant in order to recover electricity through combustion which replaces electricity EU mix from the grid (fossil fuel substitution effect). The parameters for collection and transport of used wood and paper is presented in Table A.3 and the share of post-consumer waste combusted for energy recovery in three wood utilization scenarios is shown in Table 1. The incineration of a tonne of mixed paper waste generates about 4.32 $GJ_e$ (see list of abbreviations below) of electricity (1200 kWh), assuming an electrical combustion efficiency of 24% for mixed municipal waste from paper industry (Laurijssen et al., 2010). The incineration of 1 tonne of post-consumer paper avoids emissions of 551 $kgCO_2$-eq (469 $kgCO_2$-eq/t used paper, including emissions from collection and transport). The combustion of 1 tonne of mixed post-consumer wood waste (i.e. used wood based panels and lumber) generates about 6.48 $GJ_e$ (1800 kWh) of electricity (using a 36% electrical combustion efficiency rate; Mann and Spath, 1997;

Dornburg et al., 2006). Therefore, the combustion of 1 tonne of post-consumer wood waste avoids emissions of about 827 $kgCO_2$-eq (737 $kgCO_2$-eq/t waste wood, including emissions from collection and transport).

In 2010, about 30% (3.5 MtC) of the potential post-consumer wood and 12% (6 MtC) of post-consumer paper has been disposed of in landfill (Mantau, 2012). We assumed that landfill gas is not extracted for energy use in S0 and extracted for electricity generation in S1. The collection efficiency of landfill gas is assumed 50% with gas energy recovery efficiency at the power plant of 25% (Manfredi et al., 2009). The electricity generated is assumed to substitute for the same electricity mix used as input to the landfill. In S2, we assumed that post-consumer wood and paper wastes are diverted from landfill disposal (zero waste strategy) to material and energy production. The amount of GHG emitted from landfill disposal in S0 is the same amount of GHG emissions saved from preventing landfill disposal in S2. The GHG emissions in the landfill disposal process are taken from Manfredi et al. (2009) which includes: (1) direct emissions linked to activities at the landfill site and the degradation of the waste; (2) Indirect emissions associated with the landfill but actually taking place outside the landfill site such as production of materials and electricity used, provision of fuels used and the construction of the facilities (upstream emissions) and the offset of energy production substituted by the energy recovered at the site, e.g. electricity (downstream emissions). The parameters in the landfill disposal stage are shown in Table A.3 (see Appendix).

### 2.4. Calculation of wood use efficiency gains (cascade factor)

A MEFA approach (Fischer-Kowalski et al., 2011) has been applied to estimate the flow of wood carbon from forest ecosystems, along the different stages of industrial processing to final (end) uses, i.e. a wood resource balance. The schematic representation of woody biomass flows in and between countries is shown in Bais et al. (2015). Industrial processing of woody biomass includes sawmills, panels industry, pulp industry, paper industry and energy industry. Final (end) uses of woody biomass include wood energy (or forest bioenergy) and harvest wood products (HWPs) such as paper (e.g. newsprint and sanitary paper) and paperboards (e.g. greyboard, corrugated board and folding boxboard), semi-finished wood products (e.g. sawnwood, veneer, plywood and wood panels), and other industrial wood (e.g. poles). The cascade factor of the wood resource balance quantifies how often (cascading use) the wood biomass is utilized in a wood-based product value chain, which represents an indicator of wood use efficiency (Mantau, 2012). The cascade factor is 1.00 in the case that only virgin wood resources from trees are used, and gets higher when more industrial residues and recovered post-consumer wood are utilized. The cascading factor is calculated using the following equations (1) and (2) taken from Mantau (2012, 2015):

$$Cascades = RW + IR \tag{1}$$

$$CF = 1 + \frac{Cascades}{WR_{forest}} \tag{2}$$

where RW is recovered post-consumer wood or paper waste and IR is industrial residues (e.g. sawmill co-products) utilized for wood products or energy production. CF is the overall cascading factor or total utilization ratio for woody biomass per scenario; $WR_{forest}$ is wood resources from forest (i.e. domestic used extraction and net import). Wood resources from forest, industrial residues and recovered wood fibres are presented in MtC/year.

### 2.5. Calculation of GHG emissions reduction

#### 2.5.1. Wood sector (virgin wood material substitution)

The cradle-to-gate GHG emissions reduction in the wood sector in S1 and S2 has been calculated using the following equation (3):

$$ER_{WS} = \sum_{p=1}^{n} \%\Delta RR_p * PR_p * ER_p \tag{3}$$

where $ER_{WS}$ is the GHG emissions reduction in the wood sector, % $\Delta RR_p$ is the percent change of product's re-utilization rate between scenarios, $PR_p$ is the production of product in tonne (wet weight) and $ER_p$ is the GHG emission reductions per 1% increase use of recovered fiber input in the production of product presented in $kgCO_2$-eq/t product.

#### 2.5.2. Energy sector (fossil fuel “electricity EU mix” substitution)

The reduction on GHG emission savings in the energy sector in S1 and S2 has been estimated using equation (4) below:

$$ER_{ES} = (\Delta PR_{eWR} * EF_{eMX}) \tag{4}$$

where $ER_{ES}$ is the reduction on GHG emission savings in the energy sector from substituting electricity EU mix (in 2010) by electricity produced from combusted wood resources (i.e. post-consumer wastes and industrial residues), $\Delta PR_{eWR}$ is the change in the production of electricity produced from combusted wood resources between scenarios and $EF_{eMX}$ is the GHG emission factor of the electricity EU mix (in 2010) in $kgCO_2$-eq/kWh.

#### 2.5.3. Waste sector (prevention of landfill disposal)

The GHG emissions reduction from landfill disposal in S1 and S2 has been estimated using the following equation (5):

$$ER_{LF} = \Delta LFG_{EMI} * LFD_{PCW} \tag{5}$$

where $ER_{LF}$ is the GHG emissions reduction from landfill disposal by extracting landfill gas (LFG) for energy use in S1 or preventing landfill disposal in S2, $\Delta LFG_{EMI}$ is the change in the landfill gas emissions per tonne post-consumer waste disposal ($kgCO_2$-eq/tonne), $LFD_{PCW}$ is the amount of post-consumer waste disposed of in landfills. The methods for calculating landfill gas emissions per tonne post-consumer waste disposed of in landfill is discussed in section 2.3.5.

### 2.6. Estimation of avoided GHG emissions in the forest and harvested wood products through cascading use of wood

Forest carbon sequestration benefits from wood cascading use result from the avoided emissions associated with woody biomass that would have been harvested or used in the absence of re-use or recycling in the paper and particleboard industries. The IPCC default (immediate emissions; IPCC, 2006) has been applied to calculate avoided GHG emissions in the forest. We have compared the amount of wood harvest (or used extraction) in the reference scenario with two wood cascading use alternatives. Wood used extraction (UE) is the amount of extracted wood entering the socio-economic system (e.g. industrial wood and firewood). We also estimated the total (wood) biomass appropriated (TBA). It is the sum of used extraction (UE) and unused extraction (UnE), i.e. the amount of wood that is felled through harvest but not recovered by forest industries from the forest (e.g. logging residues and roots), which provide ecosystem services such as soil organic carbon (SOC) and nutrient cycling. The method for calculating UE, UnE and TBA has been adopted from Bais et al. (2015) study.

The GHG effects of increasing product cascading on HWPs is calculated by comparing the average annual carbon uptake (from fresh fibres) in HWPs over a period of 100 years in S0 with S1 and S2. The GHG calculations started with zero HWPs stock of wood products (e.g. sawnwood, wood based panels, paper) in the first year and end up with a certain carbon stocks for HWPs over 100 years. To account for the average annual effect, the carbon uptake in HWPs over 100 years is divided by 100 years (in $MtCO_2$-eq/year).

The stock over time in a first decay system, assuming constant annual inflow, can be written as (European Commission, 2012):

$$C(i+1) = e^{-k} \times C(i) + \left[\left(\frac{\left(1-e^{-k}\right)}{k}\right)\right] \times Inflow(i) \tag{6}$$

where $i$ is the year, $C$(i) is the carbon stock of the harvested wood products pool in the beginning of the year $i$ in MtC, k is decay constant of first-order decay given in units of year $^{-1}$ (k = ln(2)/HL, where HL is half-life of the harvested wood products pool in years), Inflow($i$) is the inflow of the harvested wood products pool during year *i in MtC/year.* Default half-life values (HL): 2 years for paper; 25 years for wood panels; 35 years for sawnwood (UNFCCC, 2011).

The build-up of product stock in a given year is the difference between the stock in the next year and the stock in a given year:

$$\Delta C(i) = C(i+1) - C(i) \tag{7}$$

The change in stock in a given year is the difference between the inflow and the outflow in that year. The outflow in year $i$ can thus be written as:

$$Outflow(i) = Inflow(i) - \Delta C(i) \tag{8}$$

### 2.7. Uncertainty estimation

In order to meet concerns about the accuracy of FAO data on wood harvest in the EU, we estimated the minimum and maximum wood fuel removals estimates which was based on an extensive literature survey (UN, 2014, 2011; FAO, 2014, 2011). To estimate the uncertainties in industrial wood removals, the volume of HWPs taken from FAO statistics (FAO, 2014) were converted to roundwood equivalent volume using forest products conversion factors (UNECE/FAO, 2010). This allows for the estimation of the primary raw materials required for HWPs production. The discrepancies between data on volumes of industrial roundwood removals from FAO statistics and calculated raw materials required (in rwe) for HWPs production allowed us to estimate the “unrecorded” industrial wood removals.

The moisture content of raw materials, technology and energy used in the production process of wood pulp (for paper production) and particleboard can vary and differ extensively across Europe. These external factors do play a major role in the GHG impacts of the production process of industrial wood products. In order to assess the uncertainty in the industrial wood products production processes as well as in the incineration and landfill disposal stages, we estimated high and low GHG emissions estimates by applying scenarios (Table 2).

## 3. Results

### 3.1. Wood use efficiency gains

The overall wood use efficiency (cascade factor) in the reference scenario (S0) is 1.65 (total wood utilization in Table 3). It decreased to 1.60 in the state-of-the-art wood and paper recycling scenario (S1) while increased to 1.71 in the optimized future wood product cascading scenario (S2). The increased product cascading or recycling in wood products resulted to an increase in the wood use efficiency from 1.09 to 1.34 (S0 to S2; 23% increased) and 1.43 in the optimized scenario (S0 to S2; 31% increased) (see Table 3.F). However, this resulted to a decreased wood use efficiency factor in the energy sector from 1.56 to 1.26 (S0 to S1; 20% decreased) and 1.43 in the optimized scenario (S0 to S2; 18% decreased) (see Table 3.G).

### 3.2. GHG emissions reduction through cascading use of wood

The GHG emissions per tonne (wet weight) woody raw material input in the wood sector is higher for virgin fibres compared to recovered fibres (or recycled fibres) especially in the processing stage (Table A.6; see Appendix). This is mainly due to less chipping and drying energy needed for processing recycled fibres because of their smaller size and lower moisture content.

The GHG emissions reduction per 1% increase of recovered fibre material input ranges from 0.82 to 6.21 $kgCO_2$-eq per tonne paper (depending on paper grade) and 3.01 $kgCO_2$-eq per tonne particleboard (Table A.7; see Appendix). Depending on the paper grade, GHG emissions savings are higher in packaging and wrapping papers (i.e. corrugated board, folding boxboard and greyboard) and lower in sanitary papers (Table A.7; Figure A.1; see Appendix). Packaging papers like corrugated and grey boards made from recovered fibre use less energy in the processing stage because it does not require a deinking process. Sanitary paper resulted in lower GHG emission savings because this type of paper commonly use pulp produced from chemical pulping, a pulping process that is self sufficient in terms of energy (Laurijssen et al., 2010). It uses energy from black liquor combustion that replaces fossil fuels (energy generated exceeds the heat demand of the pulping process). However, chemical pulping biomass input (or embodied biogenic C) is about twice as high compared to mechanical pulping. The impact of the extraction of virgin woody biomass material, collection of waste material and transportation on overall energy balances tends to be minor compared to the production processing (Figure A.1a-d; see Appendix).

The total GHG emissions (cradle-to-gate energy use) in the wood sector are reduced by 28 $MtCO_2$-eq/year (42% reduction) and 35 $MtCO_2$-eq/year (52% reduction) when comparing the reference scenario (S0) with alternative scenarios, S1 and S2, respectively (Table 4). This is mainly due to the effect of reduced virgin wood fibre input in harvested wood products (HWPs) in the scenarios S1 and S2 (Fig. 3). In contrast, the increased product cascading would result in a reduction of GHG emissions savings in the energy sector by 43 and 42 $MtCO_2$-eq/year (−49% and −48%) in scenarios S1 and S2 (Table 4) due to reduction of feedstocks from recovered post-consumer wood, post-consumer paper and industrial residues (Fig. 4a–c). This reduction is compensated by increased utilization of virgin wood (i.e. additional wood fuel removals) for energy production (Figs. 3 and 4).

Since cascaded wood products (i.e. particleboard produced from recovered material input) will eventually be recovered for energy generation, the future supply of material for energy in S2 would be increased by 21% with additional future GHG emission savings in the energy sector by 2.05 $MtCO_2$-eq/year, assuming incineration or combustion technology (36% electrical combustion efficiency) and electricity EU mix (451 $gCO_2$-eq/kWh) remain the same. Assuming future electrical combustion efficiency increased to 48% (BIG-CC power plant efficiency ranging from 48% to 59%; Laurijssen et al., 2010) and future GHG emissions/kWh electricity EU mix decreased to 392 $gCO_2$-eq/kWh (estimated in 2030; Figure A.2; see

**Table 2**
Description of the scenarios for the assessment of the uncertainty in the wood pulp and particleboard production processes, combustion/incineration and landfill disposal stages.

| Process | High emissions estimate | Low emissions estimate |
|---|---|---|
| Particleboard production process | Moisture content of woodchips (drying process): virgin wood chips (60%) vs recovered wood chips (15%) | Moisture content of woodchips (drying process): virgin wood chips (40%) vs recovered wood chips (25%) |
| Wood pulp production process | Energy used in pulping process:<br>- steam: natural gas<br>- electricity: EU mix | Energy used in pulping process:<br>- generated energy from combustion of industrial residues assumed substitute natural gas and electricity EU mix |
| Combustion/ incineration | Incineration power plant with electrical combustion efficiency of 24% [a] for mixed wood waste incineration | Biomass integrated gasification combined cycle (BIG-CC) power plant (wood combustion) with electrical combustion efficiency of 48%[a] for waste wood |
| Landfill disposal -applied to: S0 (emissions); S2 (avoided emissions) | Conventional landfill without energy recovery<br>-0% collection efficiency [b] | Conventional landfill (with flare) without energy recovery:<br>-80% average collection efficiency over 100 years<br>- collected gas converted to biogenic $CO_2$ in flare with 99% conversion efficiency [b] |
| -applied to S1 | Engineered landfill with energy recovery:<br>- 50% average collection efficiency over 100 years<br>- no conversion of $CH_4$ to biogenic $CO_2$ in flare<br>- 25% gas recovery efficiency at the power plant (EU electricity mixed input substitution)[b] | Engineered landfill with energy recovery:<br>-80% average collection efficiency over 100 years<br>- with conversion of $CH_4$ to biogenic $CO_2$ in flare with 99% conversion efficiency<br>- 35% gas recovery efficiency at the power plant (EU electricity mixed input substitution)[b] |

[a] Laurijssen et al., 2010.
[b] Manfredi et al., 2009.

**Table 3**
Wood Carbon stocks and cascade factor of the EU wood resource balance for a reference case and two wood cascading use scenarios.

| Item | Total wood resource balance | | | | | |
|---|---|---|---|---|---|---|
| | Reference use, without product cascading (S0) | | State of the art wood and paper recycling (S1) | | Optimized future wood product cascading (S2) | |
| | MtC | Factor[a] | MtC | Factor[a] | MtC | Factor[a] |
| Wood resources (WR) from forests[b] (domestic used extraction + net import) | 140 ± 14 | | 140 ± 14 | | 130 ± 14 | |
| B. Industrial residues in wood products ($IR_1$) | 12 | | 12 | | 12 | |
| C. Industrial residues in energy ($IR_2$) | 33 | | 27 | | 25 | |
| D. Recycling in wood products ($RW_1$) | 0 | | 36 | | 44[c] | |
| E. Recovery in energy ($RW_2$) | 46 | | 10 | | 12[c] | |
| ***F. Cascades in wood products***[a] | ***12*** | ***1.09*** | ***48*** | ***1.34*** | ***56*** | ***1.43*** |
| *G. Residues + recovered wood in energy* | *79* | *1.56* | *37* | *1.26* | *37* | *1.28* |
| **Total cascade factor (CF)** | | **1.65** | | **1.60** | | **1.71** |

[a] Cascades = industrial wood residues (IR)+ recovered wood fibres (RW); CF = 1 + (cascades/wood resources from forests).
[b] Domestic used extraction includes industrial roundwood removals and additional wood fuel removals (see Fig. 4).
[c] Diversion of wood waste from landfill disposal to energy recovery (zero waste strategy) has taken into account.

Appendix), the additional future GHG emission savings in the energy sector in S2 would be 2.23 $MtCO_2$-eq/year.

The average annual avoided GHG emissions from landfill gas extraction for energy generation (electricity EU mix substitution) in S1 is 7 $MtCO_2$-eq and from prevention of landfill disposal in S2 is 13 $MtCO_2$-eq (Table 4).

### 3.3. Avoided GHG emissions in the forest and harvested wood products through cascading use of wood

The total wood C savings in the forest (or avoided emissions in the forest) is estimated to be 10 MtC/year (or 37 $MtCO_2$/year) when the used extraction of the reference scenario (S0; Fig. 4a) has been compared with the optimized product cascading scenario (S2; Fig. 4c). This is about 8% reduction on wood used extraction and total wood biomass appropriated (Fig. 4).

The increased product cascading in the wood sector resulted in the reduction of industrial roundwood removals by 42 MtC/year (154 $MtCO_2$/year; 30% reduction) and 53 MtC/year (194 $MtCO_2$/year; 38% reduction) in scenarios S1 and S2, respectively. This is the effect of reduced harvest volumes and thus trees left standing in the forest (if wood C savings will not be used for other purposes like energy use). Additionally, increase product cascading in the wood sector resulted to a reduction of average annual carbon uptake (from fresh fibres) in HWPs by 14% (675 $MtCO_2$-eq/year) and 17% (834 $MtCO_2$-eq/year) in scenarios S1 and S2 (compared with S0), respectively (Figure A.3; see Appendix).

## 4. Discussion

### 4.1. Potential benefits of cascading use of wood biomass

Optimized wood product cascading has potential to increase the overall wood use efficiency by 4% (cascade factor from 1.65 in S0 to 1.71 in S2) and reduce GHG emissions in the European wood sector by 52%, compared with no product cascading scenario (S0). Optimized cascading use in the wood sector brings not only important benefits in terms of material and energy savings but also avoidance of GHG emissions in the forest and landfill (Figs. 3, 4; Tables 3 and 4). However, the reduction of feedstock of the energy sector due to increased material recycling may be compensated by either utilization of fossil fuel or virgin wood. As showed in Figs. 3 and 4, the increased utilization of recovered wood for paper and particleboard production resulted in increased use of virgin wood for energy use

**Table 4**
GHG emissions reduction through virgin wood material substitution, fossil fuel substitution and prevention of landfill disposal in two wood cascading use scenarios: state-of-the-art wood and paper recycling (S1) and optimized future product cascading (S2) as compared with no product cascading scenario (S0).

| Sector/Item | GHG emissions reduction/savings (S0 vs S1) | | GHG emissions reduction/savings (S0 vs S2) | |
|---|---|---|---|---|
| | $MtCO_2$-eq/year | % | $MtCO_2$-eq/year | % |
| **1. Wood sector (virgin wood material substitution)** | | | | |
| Cradle-to-gate energy use | | | | |
| - particleboard production | 3 ± 3 | 14% | 5 ± 4 | 21% |
| - wood pulp production | 25 ± 19 | 56% | 30 ± 25 | 68% |
| ***GHG emissions reduction in the wood sector*** | ***28 ± 22*** | ***42%*** | ***35 ± 29*** | ***52%*** |
| **2. Energy sector (fossil fuel "electricity EU mix" substitution)** | | | | |
| Incineration with energy recovery (i.e. electricity) | | | | |
| - post-consumer wood/paper | −36 ± 2 | −75% | −33 ± 1 | −69% |
| - sawmill residues & bark | −7±2 | −18% | −9±3 | −23% |
| ***Reduction on GHG savings in the energy sector*** | ***−43 ± 4*** | ***−49%*** | ***−42 ± 4*** | ***−48%*** |
| **3. Waste sector (landfill gas extraction for electricity generation in S1 and prevention from landfill disposal in S2)** | | | | |
| Landfill gas emissions | | | | |
| - post-consumer wood | 3 ± 7[a] | 48% | 5±6[b] | 100% |
| - post-consumer paper | 4 ± 10[a] | 47% | 8±9[b] | 100% |
| ***Avoided GHG emissions in the waste sector*** | ***7 ± 17***[a] | ***48%*** | ***13 ± 15***[b] | ***100%*** |

[a] Avoided GHG emissions from extraction of landfill gas for electricity generation (replacing electricity EU mix within the process).
[b] Avoided GHG emissions from the prevention of landfill disposal.

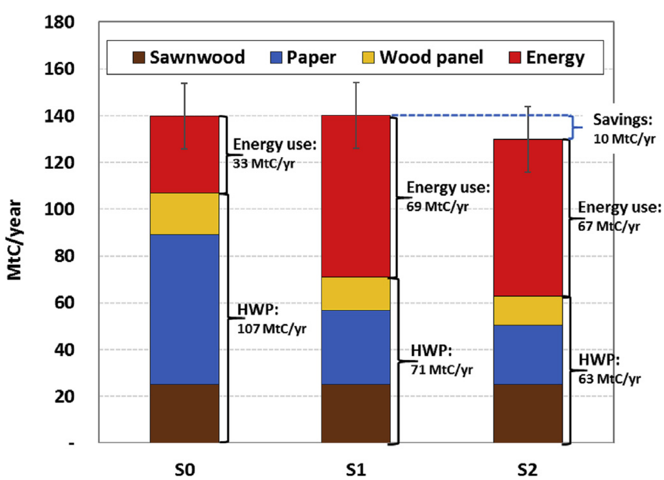


**Fig. 3.** Total wood resources (i.e. domestic use extraction and net import) in Mega tonne Carbon per year showing different wood uses in three wood utilization scenarios: no product cascading (S0), state-of-the-art wood and paper recycling (S1) and optimized product cascading (S2). (Wood harvest includes "unrecorded" industrial roundwood removals (31 MtC) for HWPs production; error bar indicates high and low wood fuel removal estimates in 2010).

due to reduction of recovered fibre in the energy sector in the scenarios S1 and S2 (Fig. 4). Wood harvested for energy is regarded as an immediate emission while wood products will release $CO_2$ over time (UNFCCC, 2011). The environmental impacts of increased harvest for energy use has been heavily debated; some sources state even that regrowth of harvested forest stand can take several decades, i.e. the long term carbon debt and parity discussion (Mitchell et al., 2012). For the European forests, it is estimated that the maximum needed regrowth time (to compensate for immediate emissions) is 10 years for harvesting residues, 80 years for roundwood from increased thinnings and 180 years for roundwood from final fellings in a coal substitution scenario (Nabuurs et al., 2017).

The exact impact and time required to compensate for forest carbon changes depend on many different factors, such as growing conditions, forest age, tree species harvested, forest management and practices and frequency of disturbances (i.e. fire and insect infestation; Ter-Mikaelian et al., 2013; Kaipainen et al., 2004; Liski et al., 2001). Length of the rotation period is also a decisive variable (Kaipainen et al., 2004; Liski et al., 2001), however the mean annual carbon uptake eventually will decline with increasing rotation time as trees become less productive especially when stands reach a mature development stage, thus reducing the annual carbon uptake by the forest ecosystems in the course of time (Jandl et al., 2007). The complex interplay of these factors results in an intricate relationship between current wood harvest and carbon stocks lost in forests. Nevertheless, due to product cascading, the negative environmental effects of wood harvesting is counterbalanced by the prolonged carbon storage in the harvested wood products, thereby contributing to the mitigation of climate change.

Though a reduction of recovered wood utilized in the energy sector might result in increased product recycling (optimized wood product cascading), one can assume that cascaded products will eventually be utilized for energy use in later stages (with the product end-of-life). This may eventually result in an increased future supply of wood in the energy sector in later stages. In consequence, this time-lag dynamic renders wood cascading not an adequate short term renewable energy strategy. Rather it results in a postponement of avoided $CO_2$ emissions achieved by energy sector which renders it a strategy suitable for long-term goals.

Actually, increased cascading use in the wood sector decreased the new carbon uptake from fresh fibres in HWPs in our analysis (Fig. 3, A.3). Harvested wood products that remain in use for many years are a significant pool of existing carbon, and the release of that carbon is delayed due to a second life. There will be a reduction of wood harvest for wood products production when product cascading has been increased, assuming the demand for wood resource remain the same (Figs. 3 and 4).

### 4.2. Challenges of optimizing the cascading use of wood biomass

Paper and particleboard production from recovered fibres is a promising option for reducing energy consumption and GHG emissions (Fig. 3), however the availability of recovered fibres is

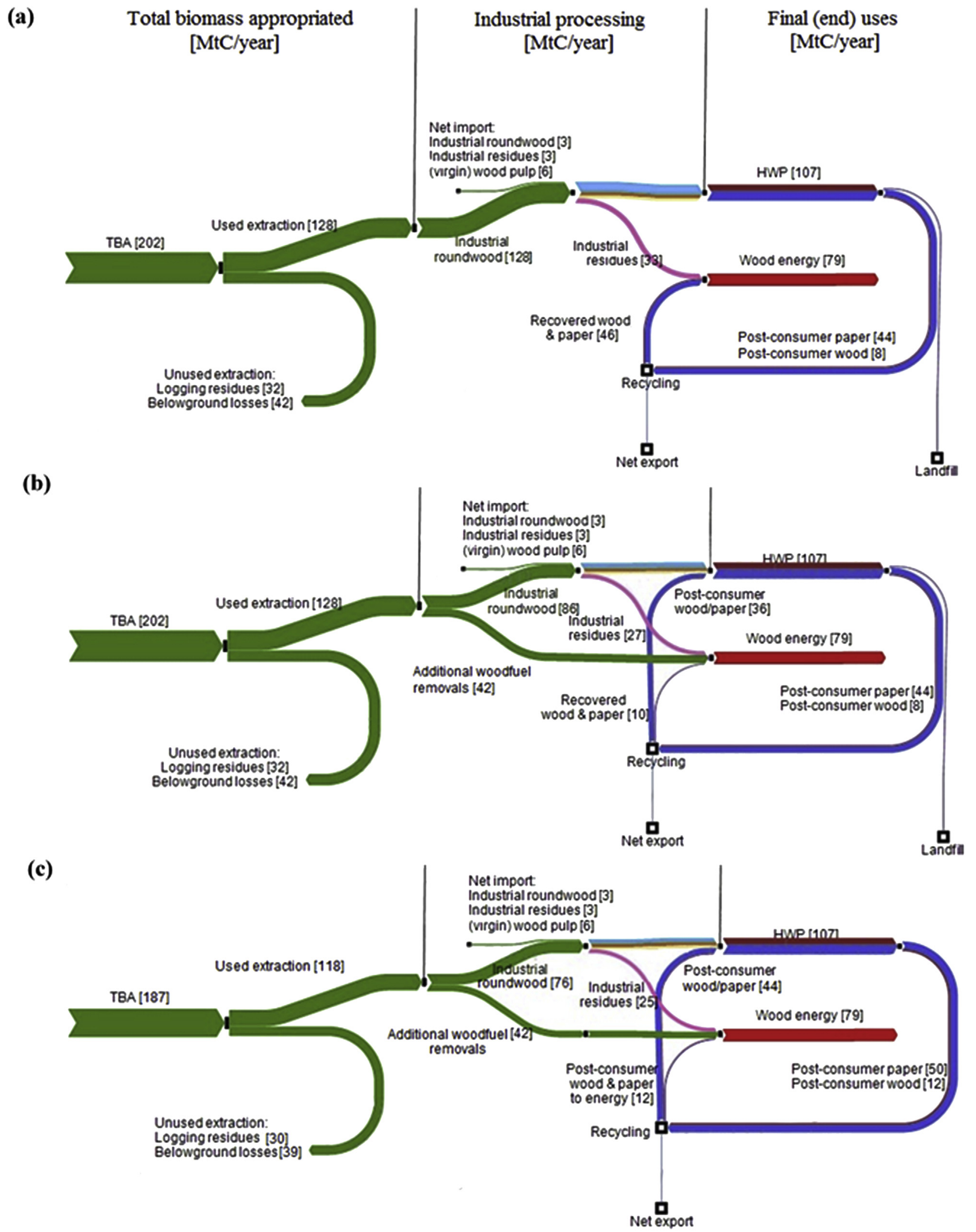


**Fig. 4.** Wood C flows in the EU in three wood utilization scenarios: (a) S0 no product cascading; (b) S1 state-of-the-art wood and paper recycling; (c) S2 optimized product cascading. TBA – total biomass appropriated; HWP – harvested wood products. ("Unrecorded" industrial roundwood removals (6 MtC) is already included).

sometimes limited. Increasing the re-utilization rates beyond certain limits also requires the exploitation of resources. Certain factors do have in limiting influence on the possibility of an extended use of recovered fibre, such as the low quality of

recovered fibres, poor sorting, price for the recovered fibre, etc. (Miranda et al., 2010; Vis et al., 2016).

Improved efficiency allows consumers to save money, enabling them to consume more products or bioenergy, which could lead to the so-called "rebound effect". The rebound effect is defined as the increase in consumption due to environmental efficiency interventions that can occur through a price reduction (i.e. efficient products being cheaper or subsidized by the government and hence more is consumed) or other behavioural responses (Maxwell et al., 2011). The further increase on wood products and bioenergy demand to support bioeconomy may affect wood use efficiency gains and GHG emissions savings due to the reduction of the share of recovered fibre in total wood products production. However with optimized cascading use, the wood saved could be utilized for additional wood products or bioenergy without increasing harvest pressures in forests.

### 4.3. Cascading use factor: the theory behind

We have based our cascade factor on the Mantau (2012, 2015) study (see Section 2.4). Consequently, the use of industrial by-products (industrial wood residues) in the production process in the wood resource balance is interpreted as cascade use. This does not correspond to the usual interpretation of cascade use: woody biomass should be used as material in more than one utilization phase, and burned (or landfilled) at the-end-of-life after the final phase (for example, see Höglmeier et al., 2013). The use of industrial wood residues is actually the combined use of (fresh) woody biomass and not cascaded use of old products after end-of-life (Iffland et al., 2015). Only post-consumer wood should be included in cascade use, because it does have passed through one material use phase.

The wood market balance (Knauf, 2015) is only listing of primary woody biomass (roundwood) and post-consumer wood, and leaves by-products and other industrial residues out of the balance. Also, it takes the consumption of wood products (both material and energy) into account, rather than wood input in industry and semi-finished products. On the one hand, this approach is quite sophisticated to evaluate the cascading of both wood and paper fibres: it counts only the product stages and not intermediate residue stages, as a cascading stage. On the other hand, it is a quite challenging approach, as at least the consumption and trade data for further processed products, like construction wood, furniture, finished paper products, are less complete and not readily available, in comparison with data for semi-finished wood products like sawnwood, wood based panels, wood pulp in the wood resource balance of Mantau (2012, 2015). The wood market balance approach (Knauf, 2015) can also be used for carbon management, when the carbon stored in final products is aimed for. As such, the carbon management studies could help exploring additional data sources for further processed products.

### 4.4. Uncertainties and limitations of the study

In our study, we followed simple approaches and assumptions and thus many uncertainties remain. We assumed a linear relationship between the share of recovered fibre input and the GHG emissions savings but this assumption is uncertain because as more energy might be needed for 1% extra recycling. However, in the absence of specific data we applied the same assumption, as made by Sikkema et al. (2013). In consequence, our result of GHG savings might be over-estimated. Another particular source of uncertainty is the lack of reliable data on post-consumer wood concerning its quality and use. Furthermore, there is a large variability in the transport distance and modes of use especially for the transport of recovered fibres (Eisted et al., 2009), and so transportation emission estimates given here are somewhat uncertain.

External effects (e.g. transport distance and technology development) do play a major role in the GHG impacts on the production process of paper and particleboard. For instances, the GHG emissions reduction per 1% increase of recovered fibre input per tonne of newsprint in this study (within EU-28; 5.59 kg$CO_2$-eq/tonne newsprint) is lower compared to the study in the Netherlands (14.9 kg$CO_2$-eq/tonne newsprint; from Norske Skog Parenco database in 1991–2010 cited by Sikkema et al., 2013) and higher compared to the study in Canada (between 0.15 and 4.90 kg $CO_2$-eq/tonne newsprint; Sikkema et al., 2013) (Table A.6; see Appendix). The cradle-to-gate GHG emissions reduction per 1% increase of recovered fibre input per tonne of particleboard (within EU-28; 3.01 kg$CO_2$-eq/tonne particleboard) is lower compared to a Belgian study (4.00 kg $CO_2$-eq/tonne particleboard; Fedustria database in 2011 cited by Sikkema et al., 2013) and Canada (1.69–6.77 $CO_2$-eq/tonne particleboard; Sikkema et al., 2013) (Table A.6; see Appendix). The lower value for our EU study is mainly due to the differences in the transport distances for fresh and waste fibres, processing technology, GHG emissions factor used, or other possible external factors.

This analysis is mainly focused on the domestic (within EU-28) supply of recovered fibre. Increased imports therefore may influence the GHG emissions reduction of cascading use in the wood sector due to increase transport distances and also the differences on collection and sorting technology and efficiencies. Perhaps the greatest uncertainty is in regard to assumptions regarding the forest, i.e. the fate of forest stands left to longer rotation ages and the reaction of private forest owners to potential decreases in demand for wood, while acknowledge, but not included in this analysis. The potential impacts on C balances due to these two factors alone are large. Furthermore, market structures and prices (and price differences, e.g. between biomass and fossil fuels) will play a decisive role in the establishment of efficient pathways. These and similar drivers have not been included in this analysis but require rigorous interdisciplinary research efforts that encompass forest- and biophysical expertise as well as (micro- and macro) economic perspectives.

## 5. Conclusions

In general, cascading use of woody biomass has the potential to reduce the environmental impacts related to GHG emissions and the use of wood resources. The effect of an increased wood use efficiency in the wood sector allows to enhance the availability of wood biomass for other uses and so to reduce the pressure on virgin (industrial) wood, or in reduced harvest pressure in forest ecosystems (avoided emissions from industrial wood harvest) by one-third. However, it reduces the average annual carbon uptake from fresh fibre in final products, such as paper and paperboards by one-sixth. Optimized product cascading (S1, S2) leads to further GHG emissions reduction by 42%–52% compared to the no product cascading scenario or reference scenario (S0). The use of recovered fibers in a recycled product saves energy in comparison with fresh roundwood (or industrial residues) for the production of the same type of product in the forest industries. Due to smaller size and lower moisture content of the recycled fibers, there is less chipping and drying energy needed. These gains, however, are partly counterbalanced in short term by lower GHG emissions savings in energy sector by one half (−48% to −49%) due to delayed availability of waste wood and waste paper fibers. Therefore, optimized wood product cascading (S1, S2) increases the efficiency of the resource use in general. But it can be less favourable in terms of GHG emissions reduction in the energy sector especially on meeting

short-term (2020–2030) renewable energy targets compared with the reference scenario. However, the optimized wood product cascading may lead to a long-term sustainable supply of wood for energy generation. In order to further maximize the potential benefits of cascading use of wood biomass, it is important to improve the collection efficiency by focusing on the key pre-conditions, being eco-design and traceability of materials with improved collection and sorting strategies. Moreover, measures that abate or limit rebound effects will be important, in terms of forest ecosystem protection. Otherwise, wood use efficiency gains will be offset by increased demand.

**Acknowledgements**

The authors would like to thank the anonymous reviewers for their valuable comments and suggestions. The research leading to these results has been supported by the EU through the Marie Curie Initial Training Networks (ITN) action CASTLE, grant agreement no. 316020. The authors are also grateful for funding from the European Research Council ERC-2010-Stg-263522 LUISE and the Austrian Science Funds (FWF), project number P29130-G27. The contents of this publication reflect only the author's/authors' views and the European Commission is not liable for any use that may be made of the information contained therein.

**Appendix. Supplementary data**

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.04.153.

**List of abbreviations**

| | |
|---|---|
| BIG-CC | Biomass integrated gasification combined cycle |
| C | carbon |
| CF | cascade factor |
| $CH_4$ | methane |
| CHP | combined heat and power |
| $CO_2$ | carbon dioxide |
| EoL | End-of-life |
| EU | European Union |
| EU-28 | European Union 28 member states |
| GHG | Greenhouse gas |
| GJ | Gigajoule |
| $GJ_e$ | Gigajoule of electricity (i.e. energy produced by the power companies after the conversion process) |
| HWPs | harvested wood products |
| $kgCO_2$-eq/year | kilogram Carbon dioxide equivalent per year |
| kWh | kilowatt hour |
| LC | life cycle |
| LCA | Life Cycle Assessment |
| MDF | medium density fibreboard |
| MEFA | Material- and Energy Flow Accounting |
| $MJ/m^3$ | megajoule per cubic meter |
| MJ/t | megajoule per tonne |
| MRF | material recovery facility |
| MtC/year | Million tonnes Carbon per year |
| $MtCO_2$-eq/year | Million tonnes Carbon dioxide equivalent per year |
| $N_2O$ | nitrous oxide |
| OSB | oriented strand board |
| PCP | post-consumer paper |
| PCW | post-consumer wood |
| rwe | roundwood equivalent |
| SOC | soil organic carbon |
| TBA | total biomass appropriated |
| u.b. | under bark |
| UE | used extraction |
| UnE | unused extraction |

**References**

Alakangas, E., Koponen, K., Sokka, L., Keränen, J., 2015. Classification of Used Wood to Biomass Fuel or Solid Recycled Fuel and Cascading Use in Finland. http://www.vtt.fi/inf/julkaisut/muut/2015/OA-Classification-of-used-wood.pdf (Accessed 15 January 2015).

Bais, A.L.S., Lauk, C., Kastner, T., Erb, K.-H., 2015. Global patterns and trends of wood harvest and use between 1990 and 2010. Ecol. Econ. 119, 326–337.

Bajpai, P., 2015. Management of Pulp and Paper Mill Waste. Springer International Publishing, Switzerland.

Bajpai, P., 2014. Recycling and Deinking of Recovered Paper, first ed. Elsevier Inc., MA, USA.

Brinkmann, A., 2013. Handbook on Sustainability Certification of Solid Biomass for Energy Production. NL Agency, Ministry of Economic Affairs, the Netherlands. http://english.rvo.nl/sites/default/files/2013/12/Handbook_Certification_Solid_Biomass.pdf (Accessed 24 October 2016).

CEPI, 2015. CEPI Key Statistics 2014. http://www.cepi.org/system/files/public/documents/publications/statistics/2015/Key%20Statistics%202014%20FINAL.pdf (Accessed 15 January 2016).

CEPI, 2014. Resource Efficiency in the Pulp and Paper Industry: Making More from Out Natural Resources. http://www.cepi.org/system/files/public/documents/publications/othertopics/2014/RESOURCES_EFF_CEPI.pdf (Accessed 15 March 2016).

Dias, A.C., Arroja, L., 2012. Environmental impacts of eucalypt and maritime pine wood production in Portugal. J. Clean. Prod. 37, 368–376.

Dornburg, V., Faaij, A., Meuleman, B., 2006. Optimising waste treatment systems. Part A. Methodology and technological data for optimising energy production and economic performance. Resour. Conserv. Recycl. 49, 68–88.

Dornburg, V., Faaij, A.P.C., 2005. Cost and CO2 emission reduction of biomass cascading: methodological aspects and case study of SRF poplar. Clim. Change 71, 373–408.

Eisted, R., Larsen, W.A., Christensen, T.H., 2009. Collection, transfer and transport of waste: accounting of greenhouse gases and global warming contribution. Waste Manag. Res. 27, 738–745.

EPF, 2010. Post-consumer recycled wood as a valuable resource for particleboard production. In: Eastern European-German Workshop, Poznan, 25 March 2010. European Panel Federation. http://www.itd.poznan.pl/en/Post-consumer_recycled_wood_as_a_valuable_resource_for_particleboard_production.pdf (Accessed 10 January 2016).

Erlandsson, M., Sundquist, J.-O., 2014. Environmental Consequences of Different Recycling Alternatives for Wood Waste. IVL Swedish Environmental Research Institute Ltd, Stockholm, Sweden. In a Report to a Nordic Cooperation Project on the EC Recovery Target for Construction and Demolition Waste (CDW). www.ivl.se/download/18.343dc99d14e8bb0f58b76a7/1445517707516/B2182.pdf (Accessed 11 March 2016).

Essel, R., Breitmayer, E., Carus, M., Fehrenbach, H., von Geibler, J., Bienge, K., Baur, F., 14 March 2014. Discussion Paper: Defining Cascading Use of Biomass, R&D-project "Increasing Resource Efficiency by Cascading Use of Biomass—from Theory to Practice" (FKZ 3713 44 100). Nova-Institut GmbH, Huerth, Germany. http://www.mdpi.com/1996-1073/7/11/6825/htm#sthash.urtIbXzi.dpuf (Accessed 20 September 2016).

European Commission, 2016. Clean Energy for All Europeans, vol. 2016. COM, 860 final.

European Commission, 2015. 2030 Energy Strategy. http://ec.europa.eu/energy/en/topics/energy-strategy/2030-energy-strategy (Accessed 17 September 2015).

European Commission, 2014. Towards a circular economy: a zero waste programme for Europe. In: In the Annex to the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM, 398 Final. Brussels, 2.7.2014.

European Commission, 2013. A new EU Forest Strategy: for forests and the forest-based sector. In: In the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM, 659 final. Brussels, 20.9.2013.

European Commission, 2012. Proposal for a Decision of the European Parliament and of the Council on Accounting Rules and Action Plans on Greenhouse Gas Emissions and Removals Resulting from Activities Related to Land Use, Land Use Change and Forestry. COM, 93 Final. Brussels, 12.3.2012.

European Commission, 2008. Directive 2008/98/EC on waste and repealing certain Directives (Waste framework Directive). Off. J. Eur. Union L312 (EN), 3–30.

FAO, 2014. FAOSTAT: ForesSTAT. In: FAO Forest Statistical Database. FAO, Rome. http://faostat.fao.org/site/626/default.aspx#ancor (Accessed 30 May 2014).

FAO, 2011. Global Forest Resources Assessment 2010. Main report. Food and Agriculture Organization of the United Nations, Rome, Italy.

Federal Ministry of Food, Agriculture and Consumer Protection, 2011. Forest Strategy 2020. Sustainable Forest Management – an Opportunity and a Challenge for Society. http://www.bmel.de/SharedDocs/Downloads/EN/Publications/ForestStrategy2020.pdf?__blob=publicationFile (Accessed 17 September 2015).

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., Weisz, H., 2011. Methodology and indicators of economy-wide material flow accounting. J. Ind. Ecol. 15, 855–876.

Gonzalez-Garcia, S., Berg, S., Feijoo, G., Moreira, M.T., 2009a. Environmental impacts of forest production and supply of pulpwood: Spanish and Swedish case studies. Int. J. Life Cycle Assess. 14 (4), 340–353.
Gonzalez-Garcia, S., Berg, S., Feijoo, G., Moreira, M.T., 2009b. Comparative environmental assessment of wood transport models: a case study of Swedish pulp mill. Sci. Total Environ. 407, 3530–3539.
Haberl, H., Geissler, S., 2000. Cascade utilization of biomass: strategies for a more efficient use of a scarce resource. Ecol. Eng. 16 (Suppl. 1), 111–121.
Hagemann, N., Gawel, E., Purkus, A., Pannicke, N., Hauck, J., 2016. Possible futures towards a wood-based bioeconomy: a scenario analysis for Germany. Sustainability 8, 98.
Heinimö, J., Junginger, M., 2009. Production and trading of biomass for energy – an overview of the global status. Biomass Bioenerg. 33, 1310–1320.
Höglmeier, K., Weber-Blaschke, G., Richter, K., 2016. Evaluation of wood cascading. In: Dewulf, J., de Meester, S., Alvarenga, R.A.F. (Eds.), Sustainability Assessment of Renewables –based Products: Methods and Case Studies. Jon Wiley and Sons, Ltd., UK, p. 335.
Höglmeier, K., Weber-Blaschke, G., Richter, K., 2013. Potentials for cascading of recovered wood from building deconstruction – a case for south-east Germany. Resour. Conserv. Recycl. 78, 81–91.
Iffland, K., Sherwood, J., Carus, M., Raschka, A., Farmer, T., Clark, J., Baltus, W., Busch, R., de Bie, F., Diels, L., van Haveren, J., Patel, M.K., Potthast, A., Waegeman, H., Willems, P., 2015. Definition, Calculation and Comparison of the “Biomass Utilization Efficiency (BUE)” of Various Bio-based Chemicals, Polymers and Fuels. Nova Institute for Ecology and Innovation, Hürth, Germany. http://bio-based.eu/downloads (Accessed 10 September 2016).
IPCC, 2006. IPCC Guidelines for National GHG Inventories. In: Volume 4 Agriculture, Forestry and Other Land Use. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html (Accessed 13 May 2016).
Jandl, R., Vesterdal, L., Olsson, M., Bens, O., Badeck, F., Rock, J., 2007. Carbon Sequestration and Forest Management. In: CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 2, No. 017, p. 16.
Kaipainen, T., Liski, J., Pussinen, A., Karjalainen, T., 2004. Managing carbon sinks by changing rotation length in European forests. Environ. Sci. Policy 7, 205–219.
Keegan, D., Kretschmer, B., Elbersen, B., Panoutsou, C., 2013. Cascading use: a systematic approach to biomass beyond the energy sector. Biofuels Bioprod. Bioref. 7, 193–206.
Knauf, M., 2015. An analysis of wood market balance modelling in Germany. For. Policy Econ. 50, 319–326.
Larsen, A.W., Vrgoc, M., Christensen, T.H., Lieberknecht, P., 2009. Diesel consumption in waste collection and transport and its environmental significance. Waste Manage Res. 00, 1–8.
Laudon, H., Sponseller, R.A., Lucas, R.W., Futter, M.N., Egnell, G., Bishop, K., Ågren, A., Ring, E., Högberg, P., 2011. Consequences of more intensive forestry for the sustainable management of forest soils and waters. Forests 2, 243–260.
Laurijssen, J., Marsidi, M., Westenbroek, A., Worrell, E., Faaij, A., 2010. Paper and biomass for energy? The impact of paper recycling on energy and $CO_2$ emissions. Resour. Conserv. Recycl. 54, 1208–1218.
Le Net, E., Bajric, F., Vötter, D., Berg, S., Anderson, G., Roux, S., 2011. Identification of Existing Transport Methods and Alternative Methods or New Approaches with Data about Costs, Labour Input and Energy Consumption. EFI Technical Report 76, 2011. http://www.efi.int/files/attachments/publications/eforwood/efi_tr_76.pdf (Accessed 25 January 2016).
Liski, J., Pussinen, A., Pingoud, K., Mäkipää, R., Karjalainen, T., 2001. Which rotation length is favourable for carbon sequestration? Can. J. For. Res. 31, 2004–2013.
Manfredi, S., Tonini, D., Christensen, T.H., Scharff, H., 2009. Landfilling of waste: accounting of greenhouse gases and global warming contributions. Waste Manage Res. 27, 825–836.
Mann, K., Spath, L., 1997. Life Cycle Assessment of a Biomass Gasification Combine-cycle System. Midwest Research Institute (MRI). http://www.nrel.gov/docs/legosti/fy98/23076.pdf (Accessed 15 October 2016).
Mantau, 2015. Wood flow analysis: quantification of resource potentials, cascades and carbon effects. Biomass Bioenerg. 79, 28–38.
Mantau, U., 2012. Woodflows in Europe (EU 27). Project report. Celle, Germany, p. 24. http://www.cepi.org/system/files/public/documents/publications/forest/2012/CEPIWoodFlowsinEurope2012.pdf (Accessed 30 September 2015).
Maxwell, D., Owen, P., McAndrew, L., Muehmel, K., Neubauer, A., 2011. Addressing the rebound effect. In: A Report for the European Commission DG Environment, 26 April. 2011. http://ec.europa.eu/environment/archives/eussd/pdf/rebound_effect_report.pdf (Accessed 12 April 2016).
Merrild, H., Christensen, T.H., 2009. Recycling of wood for particle board production: accounting of greenhouse gases and global warming contributions. Waste Manag. Res. 27, 781–788.
Miranda, R., Bobu, El, Grossmann, H., Stawicki, B., Blanco, A., 2010. Factors influencing a higher use of recovered paper in the European paper industry. Cell. Chem. Technol. 44 (10), 419–430.
Mitchell, S.R., Harmon, M.K., O'Connell, K.E.B., 2012. Carbon debt and carbon sequestration parity in forest bioenergy production. Glob. Change Biol. Bioenergy 4 (6), 818–827.
Müller, A., Weigelt, J., Götz, A., Schmidt, O., Lobos Alva, I., Matuschke, I., Ehling, U., Beringer, T., April 2015. The Role of Biomass in the Sustainable Development Goals: A Reality Check and Governance Implications. IASS working paper. Institute for Advanced Sustainability Studies (IASS), Potsdam. http://dx.doi.org/10.2312/iass/2015.010.
Nabuurs, G.J., Arets, E.J.M.M., Schelhaas, M.J., 2017. European forests show no carbon debt, only a long parity effect. For. Policy Econ 75, 120–125.
OVAM, 2015. Action Plan Sustainable Management of Biomass Residue Flows 2015-2020 (In Dutch). Openbare Vlaamse Afvalstoffenmaatschappij (OVAM), Mechelen, Belgium.
Petersen, A.K., Solberg, B., 2005. Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. For. Policy Econ. 7 (3), 249–259.
Proskurina, S., Sikkema, R., Heinimö, J., Vakkilainen, E., 2016. Five years left – how are the EU Member States contributing to the 20% target for EU's renewable energy consumption; the role of woody biomass. Biomass Bioenergy 95, 64–77.
Puettmann, M., Oneil, E., Bergman, R., 2013. Cradle to Gate Life Cycle Assessment of Softwood Lumber Production from the Northeast-North Central. Consortium on Research for Renewable Industrial Materials (CORRIM) Technical Report, April 2013, United States. http://www.treesearch.fs.fed.us/pubs/46316 (Accessed 15 November 2015).
Richter, K., 2016. A Comparison of National Sustainability Schemes for Solid Biomass in the EU. http://www.fern.org/sites/fern.org/files/comparison%20of%20national%20sustainability%20schemes.pdf (Accessed 24 October 2016).
Saravia-Cortez, A.M., Herva, M., García-Diéguez, Roca, E., 2013. Assessing environmental sustainability of particleboard production process by ecological footprint. J. Clean. Prod. 52, 301–308.
Sathre, R., Gustavsson, L., 2006. Energy and carbon balances of wood cascade chains. Resour. Conserv. Recycl. 47, 332–355.
Scarlat, N., Dallemand, J.-F., Monforti-Ferrario, F., Banja, M., Motola, V., 2015. Renewable energy policy overview framework and bioenergy contribution in the EU – an overview from national renewable energy action plans and progress reports. Renew. Sust. Energ. Rev. 22, 969–985.
Schweinle, J., 1996. Analyse und Bewertung der forstlichen Produktion als Grundlage für weiterführende forst- und holzwirtschaftliche Produktlinien – Analysen (Analysis and evaluation of forest production as a base for forest products). Mitteilungen der Bundesforschungsanstalt für Forst- und Holzwirtschaft. Nr. 184, September Hamburg: Kommissionsverlag Buchhandlung Max Wiedebusch.
Scott, G.M., Abubakr, S., Smith, A., 1995. Sludge characteristics and disposal alternatives for the pulp and paper industry. In: Proceedings of the 1995 International Environmental Conference. TAPPI Press, Atlanta, pp. 269–279.
Schulze, E.-D., Körner, C., Law, B.E., Haberl, H., Luyssaert, S., 2012. Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. Glob. Change Biol. Bioenergy 4, 611–616.
Schwaiger, H., Zimmer, B., 2001. A comparison of fuel consumption and greenhouse gas emissions from forest operations in Europe. In: Karjalainen, T., Zimmer, B., Berg, S., Welling, J., Schwaiger, H., Finér, l, Cortijo, P. (Eds.), Energy, Carbon and Other Material Flows in the Life Cycle Assessment of Forestry and Forest Products. European Forest Institute, Joensuu, pp. 33–50.
Sikkema, R., Dallemand, J.F., Matos, C.T., van der Velde, M., San-Miguel-Ayanz, J., 2016. How can the ambitious goals for the EU's future bioeconomy be supported by sustainable and efficient wood sourcing practices? Scand. J. For. Res. http://dx.doi.org/10.1080/02827581.2016.1240228 (online publication).
Sikkema, R., Junginger, M., McFarlane, Faaij, A., 2013. The GHG contribution of the cascaded use of harvested wood products in comparison with the use of wood for energy – a case study on available forest resources in Canada. Environ. Sci. Policy 31, 96–108.
Ter-Mikaelian, M.T., Colombo, S.J., Chen, J., 2013. Effects of harvesting on spatial and temporal diversity of carbon stocks in a boreal forest landscape. Ecol. Evol. 3 (11), 3738–3750.
UN, 2014. UNdata, Fuelwood Statistics. United Nations Statistics Division. http://data.un.org/Data.aspx?q=fuelwood&d=EDATA&f=cmID%3aFW (Accessed 05 November 2014).
UN, 2011. The European Forest Sector Outlook Study II 2010-2030. United Nations, Geneva. https://www.unece.org/fileadmin/DAM/timber/publications/sp-28.pdf (Accessed 13 September 2016).
UNECE, 2015. Trade of Roundwood and Sawnwood by Species 2010-2014. UNECE/FAO Forestry and Timber Section, Geneva, Switzerland.
UNECE/FAO, 2010. Forest Products Conversion Factors for the UNECE Region. Geneva Timber and Forest Discussion Paper 49. United Nations, Geneva. https://www.unece.org/fileadmin/DAM/timber/publications/DP-49.pdf (Accessed 15 September 2014).
UNFCCC, 2011. Revised Proposal by the Chair to Facilitate Negotiations (FCCC/KP/AWG/2011/CRP.1). http://unfccc.int/resource/docs/2011/awg16/eng/crp01.pdf (Accessed 13 May 2016).
Vis, M., Mantau, U., Allen, B., 2016. Study on the Optimised Cascading Use of Wood. No 394/PP/ENT/RCH/14/7689. Final Report. Brussels. http://ec.europa.eu/growth/tools-databases/newsroom/cf/itemdetail.cfm?item_id=8906&lang=en (Accessed 01 October 2016).
Weimar, H., 2015. Altholz- und Holzaufkommen und -verwendung in Europa (und Deutschland). Thünen Insitute, Hamburg, Germany.
WRAP, 2011. Kerbside Collections Options: Wales, p. 187. Main Report. Wales, UK. http://www.wrapcymru.org.uk/sites/files/wrap/Kerbside%20Collections.pdf (Accessed 15 September 2015).
WRAP, 2009. Wood waste Market in UK. Waste and Resources Action Programme, UK. http://www.wrap.org.uk/sites/files/wrap/Wood%20waste%20market%20in%20the%20UK.pdf (Accessed 15.September 2015).